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Maximising Distributed Generation Capacity in Deregulated Markets

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***Abstract*-- The capacity of distributed generation (DG) is set to increase significantly with much of the plant connecting to distribution networks. This paper briefly reviews the technical problems associated with the connection of DG plant at distribution-level and the mitigation strategies currently available. Further it examines the shortcomings of current connection practice in terms of the potential for inadvertently limiting network capability in absorbing new DG. Finally, it demonstrates the use of optimal power flow with a technique that could facilitate maximisation of renewable generation capacity in the deregulated electricity market.**

***Index Terms*— distributed generation, optimal power flow, power distribution.**

I. Introduction

TO enable the UK to meet its obligations under the Kyoto Protocol and, to go further to reduce CO_2 emissions by 20% by 2010, the Government has set targets for renewable energy generation. Under the Renewables Obligations [1]-[2] electricity Suppliers must ensure that 10% of the energy they provide to consumers in England and Wales (18% in Scotland) is derived from renewable resources. With existing large hydro explicitly excluded and new build unlikely, the energy will have to come from wind, wave, biomass or mini-hydro plant. Purchasing production from these resources will earn Renewable Obligation Certificates (ROCs) for the Supplier. The obligation encourages renewable developments as Suppliers failing to purchase sufficient ROCs will be liable for buy-out payments.

While the 2010 target is quite modest, the targets for later years are expected to be more significant: the Scottish Executive is currently proposing a target of 40% by 2020 [3]. Such targets will require the exploitation of a significant amount of Scotland's remaining renewable potential. The unconstrained potential has been estimated at around 59 GW supplying some 214 TWh annually and capable of producing energy at less than 7p/kWh [4]. This includes some 300 MW of small hydro, 11.5 GW of onshore wind with the remainder mostly marine-based.

The location of renewable resources and the potential capacities of new plant indicates that schemes will generally be connected to lower-voltage distribution networks rather than high-voltage transmission connections. The distribution networks were not designed to accept the power injections from distributed generation (DG) sources and their connection creates a wide range of technical problems. While a range of options exist to mitigate adverse impacts, under current commercial arrangements the developer will largely bear the financial responsibility for their implementation. The economic implications can make potential schemes less attractive and, in some instances, have been an impediment to renewable development.

This paper provides a brief review of the technical problems associated with the connection of DG, the mitigation methods currently available and examines the shortcomings of current practice in connecting DG. Finally, a new technique is outlined that could facilitate the growth of DG capacity in the deregulated electricity market.

II. Review of Distribution Network Impacts

Renewable resources are generally located in areas with low population and load densities. Historically, the distribution networks in these areas were designed to supply customer demand that tended to reduce with distance from the transmission system. The networks were operated passively to ensure that the quality of electricity supplied to customers was kept within statutory limits.

Connection of distributed generation fundamentally alters the operation of distribution networks. The changes and impacts are well-documented [5]-[7] and include bi-directional power flow, voltage rise, increased fault levels, altered transient stability and degradation of protection operation and co-ordination.

The impacts arising from an individual DG scheme undergo detailed examination when the developer applies to connect. Distribution Network Operators (DNOs) appraise requests for connection under near worst-case operating conditions to ensure that their customers' quality of supply will not be degraded during normal operation. Typically, worst-case conditions occur with the generator operating at full capacity whilst local load is at a minimum. Here the network experiences the largest reverse power flows and, consequently, the greatest local voltage change which, particularly for rural areas, tends to be the most significant factor constraining generator capacity [5].

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Developers and DNOs can make use of several techniques to reduce adverse network impacts emanating from potential schemes. These are project specific and depend on the problem at hand. Where a project would result in the violation of equipment thermal or fault level ratings, there is often no alternative to the replacement of affected equipment with new plant of sufficient rating. The voltage rise effect is currently addressed through network and generator operational changes or through asset upgrades. The operational changes include the reduction of primary substation voltage, generator export constraint or operation at leading power factor. Asset upgrades include the reinforcement of circuits or connection at higher voltage levels.

In most cases these measures allow DG connection but they come at a price: operational changes have implications for generator revenue or local quality of supply, while the asset upgrades incur significant capital costs. In particular, the added capital cost can adversely affect the economics of DG projects as current ‘deep charging’ compels developers to finance the necessary capital expenditure, as a condition of connection. Alternative ‘shallow charging’ systems under consideration would allow DNOs to fund necessary network upgrades and collect use-of-system charges from DGs [8]. While this lowers developer’s upfront costs, the DNO must justify the investment in terms of revenue benefit. Alternative means of accommodating DG that avoid network upgrades have been proposed, including intelligent generator control [9] and active voltage management.

Other than the economic impact of current mitigation measures, the present first-come first-served policy for DG development offers a potential threat to renewable development. Once a Connection Agreement is signed, the developer has guaranteed access rights to the network. Subsequent developments must not impact adversely on the access of the prior connection. This means that an early and sometimes quite minor connection can prevent development of alternative larger sites and ‘sterilise’ parts of the network.

III. Managing Multiple Developments

The current approach of DG appraisal is generally acceptable for individual connections, where the impact of the generator can be clearly identified and mitigated. However, with larger volumes of developments, not only is impact assessment a major task for DNOs but also that there is an increased risk that first-come first-served development will frustrate efforts to meet Government targets.

One of the potential means of improving the situation is for DNOs to issue guidance to developers regarding the existence, or otherwise, of spare connection capacity [8]. To do this, DNOs need to ascertain the capacity of new generation that may be connected to their distribution networks. Recent studies of the transmission network in Scotland have identified where renewable energy could be absorbed by the existing and upgraded transmission system [10]. Performing similar studies on even a small section of the distribution network is relatively more intense and time consuming given the much greater number of possible connection points and the greater influence of voltage, thermal and fault level restrictions.

To enable an effective distribution-level study, an automated analytical approach was sought. Evaluation of proprietary power-flow software packages found that few offered any degree of automation, and of these, most required a significant amount of manual preparation. A solution was developed using the industry-standard PSS/E power flow software [11] and its in-built programming capability (IPLAN) that enables dynamic alteration of simulation parameters. While the necessary data was originally entered through dialogue boxes and text files, the manual scheme for data preparation, routine execution and results extraction and analysis was considered to remain overly time-consuming and error-prone. The major improvement came though the development of bespoke Windows software that uses the PSS/E package as a power flow engine, automatically supplying data, executing analytical routines and extracting results (Fig. 1). This approach has been beneficial in ensuring effective data management, error removal, and integration of non-network-related data.

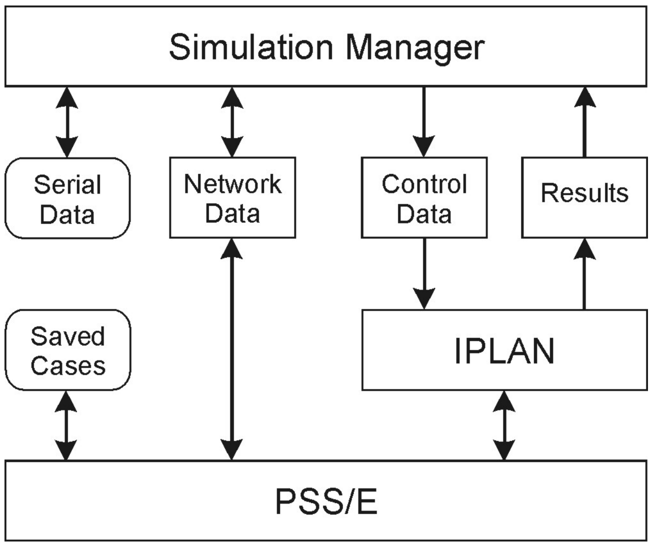

Fig. 1. Data flows between simulation manager and PSS/E

IV. Case Study System

The system used in this work is part of the UK transmission and distribution network and serves a load of around 100 MVA in a mainly rural setting. The land mass served has extensive potential for on- and offshore wind, mini-hydro and other renewable energy sources and a further 300 MW of larger centrally-dispatched generation is located in the network. Covering a wide voltage range (11 kV to 400 kV), the total circuit length exceeds 10,000 km including around 600 km at 11kV and 6,000 km at 33 kV.

For the purposes of illustration a small section of this system is used. The sub-system presented in Fig. 2 involves a section of the 132 kV sub-transmission network, the 33 kV network down to 11 kV primary sub-stations. The renewable resources situated in the vicinity of the network are shown at the possible point of connection. Furthermore, voltage variations within the full range permitted by UK statute [12] have been allowed (±6% at 11 and 33 kV).

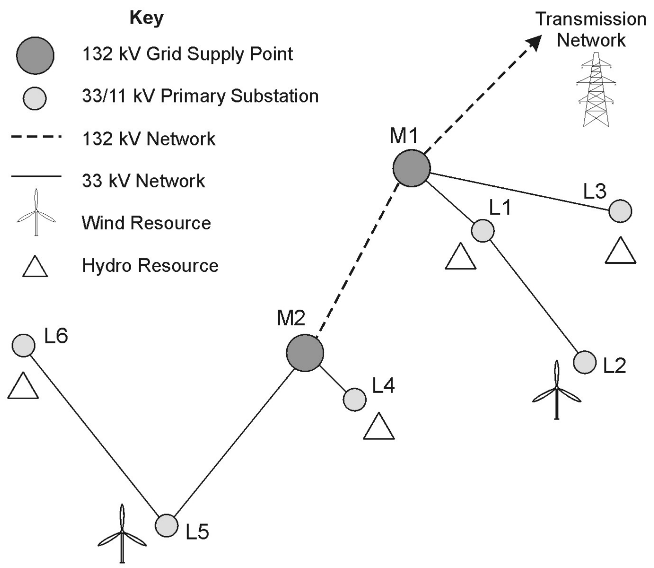

Fig. 2. Example distribution network

V. Maximising Renewable Capacity

The most basic analysis follows the approach of current appraisal practice by considering conditions with potential connection at individual locations. Routines developed enabled a location by location appraisal of the possible DG capacity that could be connected subject to the relevant constraints. The routines increment the power injections from the DG source until a constraint is violated – this defines the maximum capacity at that location. Table I shows the voltage and thermally constrained maximum capacity at each 11 kV connection point in turn with a generator operating at 0.9 lagging power factor. In most cases, the injection is constrained by the voltage at the generator terminals reaching the upper voltage limit. The exception is location L3 where the thermal limit on the 33 kV connection to M1 constrains injection. As can be seen, there is considerable variation between the volume of generation that can be absorbed at different locations. Connection applications that feature generator capacities in excess of these values will require mitigation and perhaps network reinforcement.

Table I
Maximum capacity available at individual locations

Location	Maximum Capacity (MW)	Constraint
L1	23.51	Voltage
L2	6.16	Voltage
L3	7.49	Thermal
L4	24.60	Voltage
L5	14.75	Voltage
L6	3.50	Voltage

DG development may occur at adjacent points across whole areas of the rural network, rather than isolated individual schemes. While the analysis for individual locations in Table I shows the relative sensitivity to power injection, it does not assist in explaining the potential penetration network-wide. This is because the network is highly interdependent (voltage changes at one location alter voltages elsewhere) and non-linear. Given the number of possible connection points and range of generator capacities, the establishment of maximum power injection across multiple locations is a complex and computationally intensive process. While exhaustive search techniques could be applied to very small systems, more efficient search algorithms are required.

A variety of different approaches have been used for optimisation problems in distribution systems [13]-[14]. Here Optimal Power Flow (OPF) is used to maximise capacity at specified locations. Given that such an objective function is not available with proprietary OPF packages and, with DGs tending to operate at fixed power factors, an alternative approach was necessary. This involves modelling DGs as negative loads and maximising capacity through load addition (negative load shed). The operation of this ‘reverse load-ability’ technique is illustrated through the following examples whose results are summarised in Table II.

The OPF was tested to confirm that it was able to match the power injections at the individual 11kV connection points (shown in Table I) by optimising each, in turn, under thermal and voltage constraints. In all cases, the capacities are the same (e.g. L6 in second column in Table II).

The next stage was to determine the optimal addition of capacity at two locations. As Table I indicated, locations L5 and L6 can, individually, accommodate 14.75 MW and 3.5 MW. Together, 14.85 MW located mainly at L6 can be delivered (Table II). Therefore, the connection of 3.5 MW of mini-hydro generation at L6 would, in the absence of network reinforcement, prevent later development of the larger wind resource at L5. Restricting connection at L6 to 870 kW, however, facilitates almost 14 MW of DG at L5. Hence, an overall increase in capacity is achieved by limiting generation at individual sites.

Table II
Optimal capacities at a selection of locations

Location	L6 Only (MW)	L6 & L5 (MW)	L6, L5 & L1 (MW)	L1 – L6 (MW)
L6	3.50	0.87	0.85	0.76
L5		13.98	13.19	10.13
L1			22.41	19.00
L4				18.94
L3				2.56
L2				1.65
Total	**3.50**	**14.85**	**36.45**	**53.04**

A similar picture emerges when location L1 is incorporated. The optimal capacity rises to 36.45 MW located mostly at L1, which is relatively more absorbent. Again, individual capacity is reduced in the pursuit of an increased (21.60 MW) overall maximum capacity (Table II).

The extension of the optimisation to all 11 kV substations further increases capacity. Here, a further 16.6 MW of capacity may be added to the system by reducing the individual contributions at L1, L5 and L6 (Table II). The optimal allocation of capacity mirrors the earlier individual injections with capacity tending to be sited at the more accommodating locations. This can be seen in Fig. 3 that compares the capacity added for individual power injections (Table I) with the optimal solution using OPF. Additionally, it can be seen that the OPF delivers lower injections at each point and consequently a lower overall capacity of new generation (53 MW).

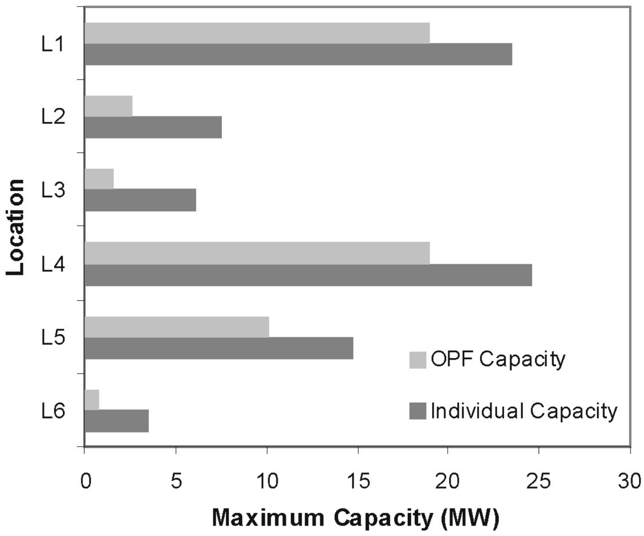

Fig. 3. OPF-derived and individual bus optimal capacities

VI. Discussion

In addition to showing the results from the example optimisations, Table II shows the progression of optimal capacity with greater numbers of locations. In each case there is a situation where the addition of generation in the network would lead to violations. Furthermore, we can see the benefit, in terms of increased overall capacity, of the trade-off of potential capacity at less absorbent sites in favour of connecting capacity at more suitable locations. Of course, this analysis considers only what the network can accept and does not take into account whether the renewable resources are available to deliver this. While the system examined here is small, the impact of encouraging development in favourable locations is clear; across a larger or regional system the potential for enhanced DG development may be significant. The technique offers DNOs a rapid, adaptable and objective means of examining the connection of distributed generation in their distribution systems. Furthermore, it facilitates the provision of information to developers regarding the best and worst places to connect renewable generation.

VII. Conclusion

The capacity of distributed generation is set to increase significantly. Here, the technical problems associated with connecting DG plant at distribution-level are reviewed. Further, mitigation strategies currently available and the shortcomings of current practice in connecting DG are examined. Finally, a new technique is outlined that could facilitate capacity DG growth. The OPF-based technique establishes the maximum DG capacities that may be connected network-wide. This can assist network operators in planning and managing DG connections as well as indicating the best and worst network locations for DG developments.

VIII. Acknowledgment

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X. Biographies

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